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Interpretations of Permissible Limits

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MUCH has been written and said concerning tables of permissible or maximum allowable concentrations of various toxic substances in air, but not enough attention has been given to their limitations and how to use them intelligently. There is a tendency to place too much reliance on figures, with little or no consideration of their real meaning.

The repeated publication of a figure often adds significance to it far beyond that intended by the original publisher. How are these figures referred to as "maximum allowable concentrations" established? What is their real meaning?

To answer these questions it is necessary first to define maximum allowable concentration. The usual definition is somewhat as follows: "The average concentration to which an industrial worker can be exposed for eight-hours daily for an indefinite period without injury or occupational disease." This definition is made up of the following items: (1) Average concentration, (2) eight-hour day, (3) indefinite exposure period, and (4) lack of injury or occupational disease. There apparently is some controversy regarding item (1), items (2) and (3) are usually accepted, and there is definite disagreement regarding the interpretation of item (4).

To reach a more satisfactory interpretation of maximum allowable concentration, attention is directed to (1) the development of tables of maximum allowable concentrations, (2) criteria on which limits are based, and (3) methods used to obtain data on which limits are based.

Historical Development

ONE of the early tables and one referred to frequently was published in 1912 by Rudolf Kobert.[1] This table is entitled "The Smallest Amounts of Noxious Industrial Gases which are Toxic and the Amounts Which May Perhaps be Endured." Concentrations are listed under four headings: (1) Rapidly fatal to man and animals, (2) dangerous in 0.5 to one hour, (3) 0.5 to one hour without serious disturbances, and (4) only minimal symptoms observed after several hours. It is evident from these headings that the values refer to acute effects and are based on toxicity. The table refers to 20 compounds, and it is interesting to note that the values for hydrochloric acid, hydrogen cyanide, ammonia, chlorine, and bromine as given under the heading "only minimal symptoms after several hours" agree with the values as usually accepted in present-day tables of maximum allowable concentrations for repeated exposures. It is also in-

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teresting to note that, with the exception of hydrogen cyanide, all of the gases have an irritating action. One other compound, carbon monoxide, has a value of 200 p. p. m., which does not greatly exceed the 100 p. p. m. usually accepted today, considering the fact that this value was published as early as 1912. However, the values for organic solvents such as benzol, carbon tetrachloride, chloroform, and carbon disulfide far exceed the values used today.

The next table, and one of the first to originate in this country, was published in Bureau of Mines Technical Paper 248[2] in 1921. This table contains 33 compounds. Much of the information was taken from the table previously referred to, with additional information from various other articles. In this table also most of the figures refer to acute toxic effects, although some information is given on the least detectable odor and least amount required to cause irritation.

In 1927 Sayers[3] published information on 27 compounds.

The data refers to (1) percentage fatal in 30 minutes or less, (2) percentage causing dangerous illness in 0.5 to one hour, (3) percentage without serious effect for 0.5 to one hour, and (4) maximum safe concentration. It is not clear whether this latter classification referred to chronic or to acute poisoning. However, it is believed that it referred to acute poisoning. Also in 1927 Henderson and Haggard[4] published information on some 25 compounds. Some of the values are listed as "maximum concentration allowable for prolonged exposure," and these values agree in most instances with values used today as maximum allowable concentrations. Other values are given for "slight symptoms after several hours exposure," and these values refer to acute exposures. In 1929 Sayers and Yant[5] published a table which lists the physiological response to various concentrations of some common gases and vapors. Seventeen compounds are listed, and the values in general refer to acute effects.

"Schaedliche Gase,"[6] published in 1931, also contains a table of toxicity values ranging, in six steps, from concentrations immediately fatal to those endured for six hours without real symptoms. Twenty compounds are included in the table. The values definitely refer to acute effects.

In 1935 Sayers and DallaValle[7] published a table containing information on "Physical and toxic properties of common vapors and gases." The table lists 37 compounds and gives information on physiological response to five levels of concentrations. The first four refer to acute effects and range from concentrations that kill in a very short time to amounts causing slight symptoms after several hours exposure. The final column. however, lists values for "maximum allowable concentration for prolonged exposure." Up to the time of the publication of this table the information given in the various tables undoubtedly referred to acute effects, even though some of the values, particularly those for several of the irritating gases, were the same as are used today for repeated exposures.

Since about 1935 most of the tables listing maximum allowable concentrations do not give a series of values for acute effects but only a single value which refers to repeated exposure. Such tables were published by Lehmann and Flury,[8] Bowditch, et al,[9] Gafafer,[10] Cook,[11] the American Conference of Governmental Industrial Hygienists,[12] and many others. The number of compounds has gradually increased and some 140 compounds are now listed.

It is evident from the foregoing that our present tables of maximum allowable concentrations have slowly evolved from earlier tables listing values pertaining primarily to acute effects and which might be considered as toxic limits. It is also evident that our present-day tables bear little resemblance to the earlier ones and contain values not based on toxic or pathological effects. However, the tendency to interpret them as relating to the toxic effect is still evident, as indicated by such state-

ments as the following: "Many of us feel that the codes on toxic limits . . ." Also, in some of the state codes, statements such as the following are noted: ". . . concentrations that equal or exceed the following, which constitute harmful exposures or harmful concentrations . . ." Also, one of the recent tables is headed "Toxic Limits of Various Substances." However, that others put a broader interpretation on the values is evident from the following: "A list of accepted and tentative values is also presented for practical use in the control of occupational disease and for the provision of both healthful and comfortable working conditions where toxic or obnoxious materials may be present," and "Considerable difficulty attends fixing . . . maximum allowable concentrations . . . because of . . . lack of uniform definition of the maximum allowable concentration concept. One concept is that the M. A. C. value should represent . . . that concentration at which a worker exposed for a sufficient period of time will just escape physiological or organic injury and occupational disease . . . A third concept is that the M. A. C. should perform the functions of the former concepts and in addition provide a working environment free of objectionable but non-injurious concentrations of smokes, dusts, irritants, and odors."

Therefore, in the evolution of tables of maximum allowable concentrations, values which are based on injury and occupational disease as well as values based on physiological effects and discomfort have been included. It might be well at this point to review briefly some of the criteria which are used in establishing permissible limits as well as the experimental procedures used to obtain the data on which the limits are based.

Criteria Used in Establishing Permissible Limits

AT LEAST three criteria have been used in establishing the maximum allowable concentrations now in use. These criteria are (1) pathological effects, (2) slight physiological effects which apparently have no discernible untoward effects on health but cause impairment of coordination and reaction time and tend to make workers more prone to accidents, and (3) discomfort or sensory effects.

In those cases where limits have been established on the basis of pathological effects, it is logical to assume that repeated exposure to concentrations significantly in excess of the allowable concentration probably would produce injury. Where the limit has been established on the basis of a slight physiological effect, it is not logical to assume that exposure to concentrations exceeding the allowable concentration would necessarily produce injurious effects.

It is quite possible that the margin between a concentration that will produce mild response and the concentration that would produce injury would be large, in which case exposure to a concentration considerably higher than the allowable concentration might not be injurious to health. The same is true for maximum allowable concentrations that have been established on the basis of sensory effects of discomfort. In this case the margin between sensory effects and actual damage to health may be even greater. It is obvious, therefore, that in using a permissible limit one must know the criterion used in establishing the limit One obviously is not justified in assuming that a hazard to health exists because the concentration exceeds the maximum allowable. However, several of the state codes state that concentrations that "equal or exceed the following shall constitute harmful exposures or harmful concentrations."

Even though maximum allowable concentrations were established with a high degree of accuracy, their interpretation must be based on the criteria used in establishing them. However, in addition to this factor one must also consider the limitations that are encountered in establishing maximum allowable concentrations and therefore it is necessary to discuss briefly the procedures used.

Procedures Used in Establishing Maximum Allowable Concentrations

MAXIMUM allowable concentrations are usually established by one of the following procedures: (1) Laboratory tests on animals, (2) laboratory tests using human subjects, (3) field investigations, and (4) a combination of all the above methods.

LABORATORY TESTS ON ANIMALS: Laboratory experiments with animals is one of the most commonly used procedure for establishing permissible concentrations and offers certain definite advantages. It is possible to control the exposures within rather accurately defined limits and to expose the animals to a wide variety of conditions. Such studies are helpful in demonstrating the nature of the damage likely to be produced, and indicate the type of response to look for in industry. By using a number of different types of animals, additional fundamental information can be obtained. The important disadvantage of the method is that it is not possible to interpret such data in terms of human response with a high degree of accuracy. This method is used particularly in establishing limits which are based on pathological effects. Limits which are established on the basis of animal experiments must be used with caution and careful observations of exposed persons should be made until experience indicates that the limit is satisfactory or should be revised.

LABORATORY TESTS USING HUMAN SUBJECTS: Laboratory tests using human subjects are usually made in establishing maximum allowable concentrations based on slight physiological effects and discomfort or sensory effects. Such tests are usually conducted after sufficient information has been obtained to indicate that such exposure of human subjects can be made with very little likelihood of injury to the subject, in other words, until evidence has been obtained that there is a definite margin between the mild physiological effect or sensory effect and possible injury. Limits based on this procedure should be fairly accurate but are subject to error, owing to the fact that the subjects usually are not accustomed to occupational exposure and therefore in some cases may tend to respond to lower concentrations than would persons working in industry. However, it is not necessary that these limits be established with a high degree of accuracy because the possibility of injury is not great.

FIELD INVESTIGATIONS: Investigations are made in industry in which the concentration of contaminant in the work atmosphere is determined and correlated with the clinical and physical examinations of the workmen. This procedure has been used in establishing initial maximum allowable concentrations for some materials and is employed to check on previously established limits. Data of this nature are being continuously obtained by many organizations that have programs which entail air analyses and medical examination of workers. In one respect this procedure can be considered the most important in establishing maximum allowable concentrations since one is working with actual conditions in industry. There are two difficulties encountered in applying the method: (1) Satisfactory sampling in order to obtain the average over-all exposure of the person, and (2) the difficulty of diagnosing injurious effects, particularly when they are of a mild or borderline degree and may be due to other factors, such as poor nutrition and general poor health. It is evident that if samples are not collected to give a good measure of over-all exposure one might set the limit too high if samples are taken at the source of contaminant and the person is not exposed to the higher concentrations most of the time and does not show signs of poisoning. Since a good average of over-all exposure is necessary in establishing the limit, obviously in evaluating exposure one should attempt to obtain a good measure of the over-all exposure.

COMBINATION OF LABORATORY AND FIELD INVESTIGATIONS: The most accurate maximum allowable concentrations are those based on both comprehensive laboratory investigations and field experience. However, regardless of the amount of information available at the time a permissible limit is established, it is always subject to readjustment if new investigations and experience indicate that the value is in error.

All maximum allowable concentrations are subject to the limitations of measuring accurately pathological or physiological response and also to the limitations of the methods of sampling and analysis of atmospheric contaminants. From a consideration of these factors, it is apparent that it is not possible to establish permissible limits with a high degree of accuracy. However, this need not detract from the use of such limits because the accuracy obtainable is satisfactory when permissible limits are used properly.

Discussion

IN APPLYING maximum allowable concentrations to interpretation of the results of air analysis, it is necessary to understand the purpose and limitations of such values as well as the limitations of the sampling and analytical procedures. While their fundamental purpose is the promotion of health and efficiency, their practical use is for guidance in establishing control procedures to prevent harmful or objectionable concentrations from accumulating. Samples may be collected to ascertain the source of contaminants or to check on control procedure. In this case, only a few samples may be taken and the analytical procedure may be relatively crude and still satisfactory results may be obtained. On the other hand, if the purpose of the sampling and analysis is to obtain data for legal purposes or for correlation with codes, careful and thorough sampling should be carried out and accurate analytical procedures should be used. Should the results of such careful sampling and analysis give results which exceed the established maximum allowable concentrations, what interpretation should be put on them?

If the permissible concentration in question has been established on the basis of slight physiological effect or discomfort, one definitely is not justified in concluding that an occupational disease is likely to occur. The same is true even though the permissible limit is based on pathological effects because one must consider not only the extent to which the values have exceeded the maximum allowable concentration but also the time factor. These factors, for example, are taken into consideration in some of the state codes, which contain statements as follows: "Temporary concentrations in excess of the maximum allowable concentrations listed shall not be permitted if exposure to such concentrations for a period of one hour or less may result in an adverse effect on health . . ." In fact, one is not justified under any circumstances in using air analysis in conjunction with maximum allowable concentrations as a diagnosis of occupational disease, nor conversely, if values are less than the maximum allowable, as evidence that occupational disease cannot occur. Obviously diagnosis of occupational disease should be based on a consideration of all factors including careful clinical and physical examinations as well as air analyses and the fundamental physiological effects of the materials in question. Maximum allowable concentrations serve as a measure of exposure similar to the determination of lead or methanol in the urine or the determination of inorganic sulfates in the urine on exposure to benzol. When used in this manner it is not necessary to place so much emphasis on the absolute value of the maximum allowable concentration. Emphasis should be placed on interpretation. This should not be taken as a criticism of existing permissible limits nor as an excuse for not establishing limits with as high degree of accuracy as possible. The values should represent our best judgment on the basis of available information and should be subject to change whenever additional ex-

perience indicates they are not satisfactory. Maximum allowable concentrations are an important tool of the industrial hygienist and to obtain the greatest value from them they should be used properly.

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Progress in Industrial Hygiene

THE primary objectives of our Association are the promotion and maintenance of health in industry and the advancement of industrial hygiene as a profession. The steady growth of the Associaton attests to the importance of the field and to the increasing recognition in industry and outside that industrial hygienists, because of their special interests, training and experience, can and do contribute uniquely to the solution of industrial health problems.

We are all aware of the great progress that has been made in the development of governmental industral hygiene services under the leadership of the U. S. Public Health Service and of the contributions which these agencies have made to the strength of the field. As a logical and most significant next step, we are now witnessing a rapid growth of industrial hygiene within industry itself, with a considerable number of such services being established during the past year. The manner in which these services are integrated into the medical and health programs in industry will be of the greatest interest.

Industrial hygiene is a unique field in that it combines into an effective unit, individuals with quite different backgrounds of training—in medicine, chemistry, and engineering. Now physics must be added to the group and the health physicists should find the activities and objectives of our Association of direct interest in parallel with their own. A number have become members of the Association already and we look forward to active participation of this new group in the affairs of the Association.

The teamwork which characterizes industrial hygiene calls for the closest professional association among the members of the team. The joint annual meeting of our Association with the industrial physicians, dentists and nurses and the American Conference group constitutes one of the most important means of maintaining and strengthening this professional relationship.

—THEODORE F. HATCH, President,
American Industrial
Hygiene Association

Personnel Protection in Industrial Radiography

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THE enormous increase in the last few years in the use of x-ray and radium for non-destructive testing and inspection in industry seems to justify a survey of the types of injury which may be produced by radiation and of preventive measures. The possible types of injury are fairly well known from medical experience since the use of x-ray and radium both as therapeutic and as diagnostic aids has resulted in a large number of injuries which have been fairly well recorded.

The first thing of real importance to remember is that the types of injuries are much the same whether the radiation is a long wave x-ray, a gamma radiation or radiation approaching the cosmic ray frequency. There are some differences quantitatively which depend upon the intensity and the penetration of the particular radiation with which you are concerned but qualitatively they are the same. As a specific example you might get a radio tumor on the skin of your hand from exposure to the comparatively non-penetrating radiation of a low voltage tube in a crystolographic outfit and you might get a tumor in the bone of your hip from the penetrating radiation of a high-powered metallographic tube but the mechanism of formation of the tumor, at least physically, would be precisely the same. The only difference would be in the depth within the body at which the radiation had its greatest effect.

Nine types of general injury have been recognized[1] which may be listed as follows: (1) x-ray dermatitis; (2) tumor induction; (3) sterility; (4) leukopenia; (5) leukemia; (6) anemia; (7) bone necrosis; (8) glandular dysfunction; and (9) fetal injury.

Since all of these types of injury have been attributed to both radiation from radium and x-radiation and since they do not normally all appear in the same individual there must be some variation in the type of injury produced by the same radiation according to the amount received in any one dose, the number and frequency of the doses, and perhaps also according to the particular individual who receives the dose.

X-ray dermatitis is generally the first thing to be seen in over-exposure to radiation of a comparatively low voltage x-ray tube. This dermatitis is characterized by a rough dry skin, keratoses—wart-like growths—and dry, brittle nails. Continued exposure may produce a malignant tumor. Quimby and Pool[2] show examples of hands with keratoses and atrophy of the skin from exposure to the ordinary medical fluoroscope. These included a case of a salesman who demonstrated his wares by holding a key in his right hand behind the screen, and another of a dental technician who held x-ray casettes in his hand during the exposure. Both of these individuals later died of radio-tumors.

Bone necrosis is very similar in form and causation to the skin conditions which have been mentioned. The foregoing reference shows an x-ray of the hand of a physician who thought it well to use the fluoroscope without protection of lead rubber gloves. Though there are dark areas in the bone, indicating excessive porosity, the description of this case says that there was no tumor at the time the x-ray picture was made.

Sterility and glandular dysfunction were treated as separate entities in the list of disabilities produced by radiation but they probably should be considered as essentially the same since sterility in this form is certainly a glandular dysfunction or nonfunction.

The question of human sterility as a result of incidental exposure to radiation in the course of a radiologist's work has

not received the study which it probably deserves since it is perfectly well known that an adequate dose of radiation delivered at one time will result in permanent sterility in either male or female. One rather extensive study was carried out by Hickey and Hall[3] for the Committee on Sex of the National Research Council. They reported that 36% of the couples investigated were childless and that of the ones who were not childless the average was 2.2 children per couple as contrasted to an average of 3.0 children per couple among other physicians similar income and age.

All of the types of injury which have been mentioned may be and usually are produced by the local irradiation of a particular tissue with a comparatively narrow beam of x-ray. In industrial practice they are the sort of thing which would be expected to develop rather promptly in an individual who interposed some part of his body into the path of the useful beam. There is another set of conditions which are more apt to be seen when the radiation is spread over the whole body in the form of a wide beam. These conditions are probably much more dangerous than the one mentioned previously since they do not produce any immediate visible signs. Some of the long range effects of such irradiation may not be seen for a number of years after the damage is done.

Among these effects of general radiation it probably looks a little peculiar in the listing to see leukopenia, meaning a shortage of white blood cells, on one line and leukemia, meaning essentially an over production of white cells, on the next line but it seems that the radiation stimulates the production before the quantity is sufficient to produce damage to reduce the production. It is a general rule that lymphatic tissue is especially sensitive to radiation both in the stimulation produced by a little bit and in the destruction produced by a little bit more.

Whatever the peculiarity in the appearance of two opposite effects as signs of the same type of damage, there does not seem to be much doubt of the fact that they are both actually produced. It was already demonstrated in 1904 that leukopenia could be produced experimentally by whole body irradiation of rabbits. More recently a study of the deaths of physicians in the 15 year period prior to 1944[4] showed that the leukemia rate in the radiologists was just 10 times that in the physician not engaging in radiology. In actual numbers this amounted to eight leukemia deaths among 175 deaths of radiologists but the chance of having these eight deaths in 175 cases purely by chance is only one in 1,300,000.

The bone marrow is also rather readily affected by radiation so that a common effect of whole body irradiation is anemia due to failure of the production of red cells. A type of anemia due to too rapid destruction of the red cells is sometimes the effect of local irradiation.

In addition to these comparatively well-known and well-understood effects there is the possibility of direct fetal injury as the result of pre-natal irradiation. I don't know how a direct fetal injury could be differentiated from a slight mutation in a good many cases—which may well be one of the reasons that this is one of the less well understood effects. Going back to the work of Hickey and Hall[3] however, they found that of the children born to radialogists before their radiation experience 2.6% were obviously abnormal. After the beginning of their exposure to radiation 4.0% of their offspring were defective.

It is generally much easier to answer this type of a question with someone other than humans as the subject of the inquiry. The famous fruit fly has been the subject of this type of experiment, as of so many others. Of course, a lot of other organisms have been subjected to x-radiation in the expectation of producing permanent genetic effects, and generally successfully, but it has been easiest to show the effects in detail with the drosophilia because of the giant chromosomes and the short gener-

ations. A variety of types of radiation injury have been demonstrated with this little fly and Fig. 1 gives some of the types of mutations which have been shown.

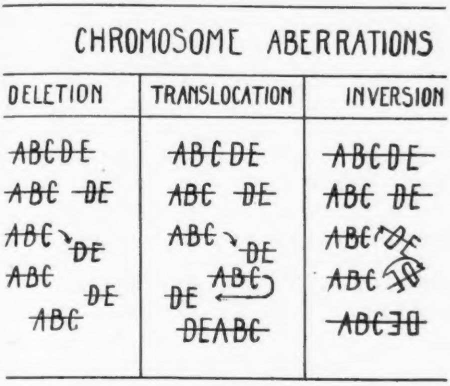


Fig. 1.

Illustrations of various kinds of chromosome aberration. The letters in each instance represent genes located on chromosome fibers. The dotted lines show where breaks have been produced in the chromosomes. In the case of deletion, parts of the chromosome, including genes, are lost. Parts of the chromosome including genes are located in new places along the main chromosome in the case of translocation. In inversion a part of the chromosome with its genes becomes reversed end for end.

From Paul S. Henshaw, Biological Significance of the Tolerance Dose in X-Ray and Radium Protection. J. Nat. Cancer Ins. 1;789-805 (June 1941)

These are chromosome aberrations but direct gene changes can also be demonstrated. The gene aberrations can be demonstrated most readily and easily since the changes can actually be seen microscopically in the giant chromosomes of the fruit fly.

One of the most interesting things about these experiments is that if the rate of occurrence of mutations is plotted against exposure there is no evidence of a threshold effect. This means very simply that a given dose of radiation will have the same effect in the production of genetic changes whether it is applied in a few minutes, a few hours, or a few months. I do not know what the dose is to produce a measurable change but in the fruit fly a dose of 35 to 40 roentgens will double the mutation rate and for other species it should be at least of the same order of magnitude. The main point is that while we will talk about tolerance doses there is no such thing as a tolernance dose so far as these particular changes are concerned.

There is some room for debate as to whether this is a hazard. We are all subjected, from birth to death, to the effects of the cosmic radiation which certainly has some genetic effect so that the question here is really what we can stand in the way of speeding up this perfectly normal process without getting the race into more trouble than it is in at the moment.

The realization of the need for protection from radiation injury came very early in the history of the utilization of penetrating radiations since a William Grube of Chicago, one the earliest makers of tubes, was seeking treatment for a typical radio dermatitis and speculating about methods for preventing further injury within a year after Roentgen first announced the discovery of the x-ray. There was no very practical suggestion about protection in the literature, however, until 1902. At that time the test was given that if a photographic plate exposed to the radiation at the point where work was to

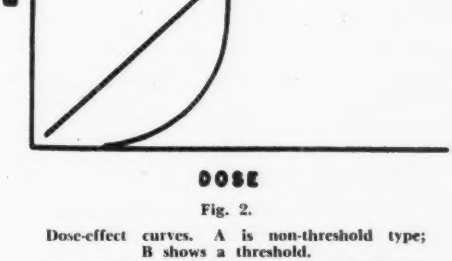


Fig. 2.

Dose-effect curves. A is non-threshold type; B shows a threshold.

From Paul S. Henshaw, Biological Significance of the Tolerance Dose in X-Ray and Radium Protection. J. Nat. Cancer Ins. 1;789-805 (June 1941)

be done was not fogged in seven minutes the radiation was not sufficiently intense to be harmful. After this one suggestion nothing further appeared in the literature until about 1915 when the Protection Committee of the British Roentgen Ray Society was founded.

The first really effective organized steps for radium and x-ray protection were actually taken in the organization of the Protection Committee of the American Roentgen Ray Society in 1920. The British Protection Committee had done little or nothing and had practically lapsed since its formation but it was re-activated in 1921. These committees were organized to provide a protection which would prevent "visible injury to the superficial tissues, derangement of the internal organs and changes in the blood" and the first requirement was to set up a value for the maximum amount of radiation which could be absorbed without producing these harmful effects, even if the exposure were long continued or frequently repeated.

Table 1 shows values of the tolerance dose which have been suggested by various authorities since 1925. There is rather remarkable unanimity among these values when one considers the difficulties which are involved in the calculations. Usually it is done by estimating the radiation which has effected workers in the field who are known to be in good health after a number of years of experience. There are only a limited number of such individuals to work with and the estimation of the radiation which they have received is a rather uncertain business at the best.

TABLE I.

Author	Date	Erythema Per Month	Dose Per Day
Mutscheller (5)	1925	0.01	0.2
Sievert (6)	1925	0.01	0.2
Glockler and Kaupp (7)	1925	0.01	0.2
Barclay and Cox (8)	1928	0.0084	0.108
Bouwers and Van der Tuuk (9)	1930	0.01	0.2
Failla (17)	1932	0.001	0.02
American Standards Association (10)	1946	0.05	0.1
National Research Council of Canada (11)	1946	0.0025	0.05

The other basis which has received a lot of consideration in the past, although it is not considered so important now, is the percentage of an erythema dose which is received in one month. This is considered the recovery time from a mild x-ray erythema and the skin dose is considered to be cumulative for a month. The third column in Table 1 gives the fraction of a monthly erythema dose which is permitted daily under the limits proposed by the various authorities.

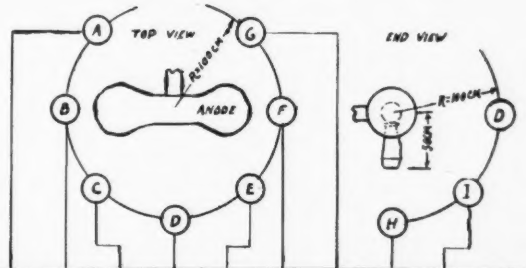
The value for the maximum permissible dosage which is most used in this country at the present time and the value which has been accepted by the American Standards Association Committee on X-Ray and Radium Protection for inclusion in the American War Standards on this subject is 125 milliroentgens per hour or 1/10 roentgens per day for continuing exposures of not more than eight hours per day.

The methods for keeping exposures down to this value if you are working around radiological equipment are shielding it sufficiently to keep the radiation inside the shield or keeping far enough away from the tube to let the inverse square law take care of you. In most practical cases it is actually necessary to have recourse to both methods. One should say immediately that it is a very good idea to have the x-ray tube on the ground floor and point the useful beam into the ground or even down into a pit as is a rather common practice with some of the high power industrial installations.

The first real advance in the provision of protection from x-ray tubes came with the introduction of the "shock-proof" tube stand in which the tube was completely enclosed in shielding for the protection of the operator. Fig. 3[12] shows the result of a stray radiation survey around a number of 200-kilvolt tubes operating in shock-proof tube stands. None of these 200-kilovolt tubes were even approaching a condition in which it is safe to work at a range of one meter from the tube and it is obvious from a glance at the data that

COMPARISON OF STRAY RADIATION FROM VARIOUS TYPES OF 200 KV. SHOCKPROOF TUBE STANDS

-NOTE-
MEASURED AT 1M FOCAL DISTANCE
WITH LEAD SHUTTER CLOSED
THE STRAY RADIATION IS INDICATED
IN ROENTGENS/HOUR
FOR IDENTICAL OPERATING CONDITIONS
200 KV. 7MM CU + 1MM AL AND 30r/MIN AT
50CM DISTANCE



NO	TYPE OF TUBE STAND	A	B	C	D	E	F	G	H	I	AVER. r/HOUR
I	AIR INSULATED TUBE HEAD		.54		.28		.42		.19		.33
II	SAME AS NO I WITH ADDED PROTECTION	.07	.21	.17	.31	.21	.18	.14	.09	.12	.17
III	AIR INSULATED TUBE HEAD		2.4		.60		.85				1.28
IV	OIL INSULATED TUBE HEAD (LARGE)	1.03	.09	1.65	2.12	2.12	.28	2.65	.74	1.30	1.33
V	SAME AS NO IV WITH ADDED PROTECTION	.39	.09	.68	1.06	1.12	.22	1.27	.63	.85	.72
VI	OIL INSULATED TUBE HEAD (SMALL)	.24	.08	.16	.10	.09	.03	.20	.20	.37	.16
VII	OIL INSULATED TUBE HEAD (SMALL)	.03	.36	.12	.05	.05	.17	.03	.02	.05	.10
VIII	SELF CONTAINED UNIT	(5.67)	(.76)	(3.57)	(6.22)	(2.84)	(.37)	(5.30)	(1.03)	(6.60)	(3.60)
IX	SELF CONTAINED UNIT	(.07)	(.08)	(.14)	(.41)	(.35)	(.04)	(.11)	(.04)	(.10)	(.16)

Fig. 3.

Taken from C. B. Braestrup, "A Stray Radiation Survey of Twenty High Voltage Roentgen Installations." Radiology 31:206

the shielding is grossly inadequate directly behind the target and at the point where it is penetrated by the electrodes.

It would be, of course, quite possible to work in perfect safety around any one of these tubes if one stayed far enough from the tube head. Say for the sake of argument that we wished to work directly back of the target of the worst one without getting a dose of more than 1/10 roentgen per day. Assuming the inverse square law for the moment, the distance is simply the square root of the quotient of 2.12 (the dosage in roentgens per hour at one meter) divided by 0.0125 (the permissible dose in roentgens per hour) or slightly over 13 meters. So if one chose to maintain a respect for distance of about 42 ft. 6 in. from this machine he would not have to worry about it at all.

It might be desirable to do a little work in the vicinity while the tube was in operation or it might just not be convenient to house the tube in a room of sufficient size all for itself. In that case it would be desirable to put up a barrier of material which attenuates the radiation more rapidly than does air. Whatever the material of the barrier it has to accomplish the same result, which is the reduction of the dosage to 125 milliroentgens per hour at the worst position. At one meter the reduction factor is again 2.12 over 0.0125 or 170. As a matter of convenience it is common to express this reduction factor in terms of the number of half-value layers of the protective material. Each thickness of one half-value layer will reduce any incidence radiation to one-half its original value. Another layer will reduce it to one-half of what remains or one-fourth of the original intensity and so on. In this instance the number (n) of half value layers will be given by 170 equals 2 to the power (n). Thus for all practical purposes (n) is 13. The thickness of protective material cor-

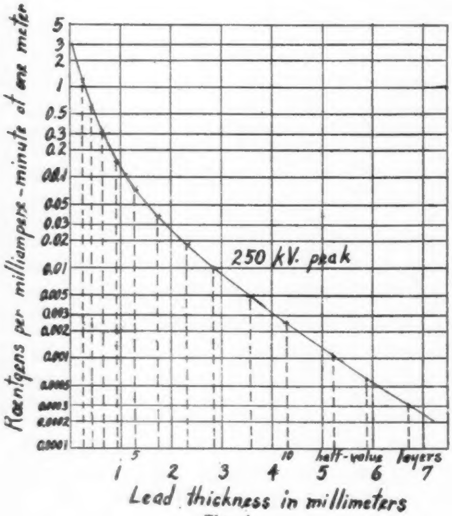


Fig. 4.

Absorption curve for 250 KV roentgen radiation in lead with the half-value layers indicated.

Adapted from the American Standards Association Safety Code for the Industrial Use of X-Rays. American War Standard Z54.1-1946

responding to the required number of half-value layers can then be picked off a chart which is shown in Fig. 4 adapted from Braestrup[15].

This calculation probably looks a little complex but as is illustrated in Fig. 5[13] it can be read directly from the scales of a slide-rule without even the trouble of setting the slide with the exception of the plot of percentage transmission against thickness of the protective material.

It is quite essential that an experimentally made plot of percentage transmission be used and that it be made for radiation of approximately the quality against which protection is to be provided. There is a very considerable change in the thickness of the half value layer as you increase the voltage of the tube as shown in Fig. 5.[14]

The structural material of the building will have some value as shielding in addition to the lead which one usually thinks of as protection against radiation and if the potential is very high it may be necessary to rely on building materials for a large part of the protective job because of the great weight and expense of a heavy metal shield. Fig. 6[2] shows graphically the

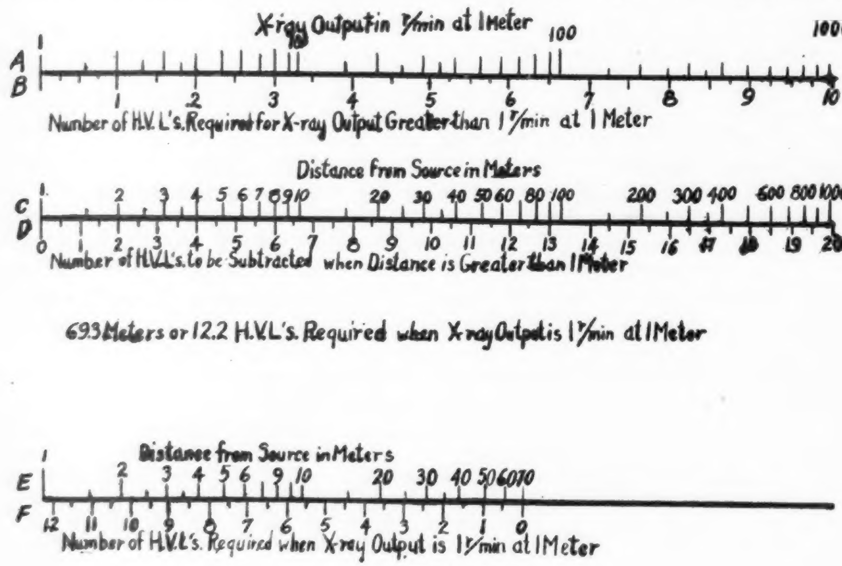


Fig. 5.

Method of calculation of the radiation protection required directly from the scales of a slide rule.

From G. Failla, "Protection against High Energy Roentgen Rays." Am. J. Roent. Rad. Therapy 54:533

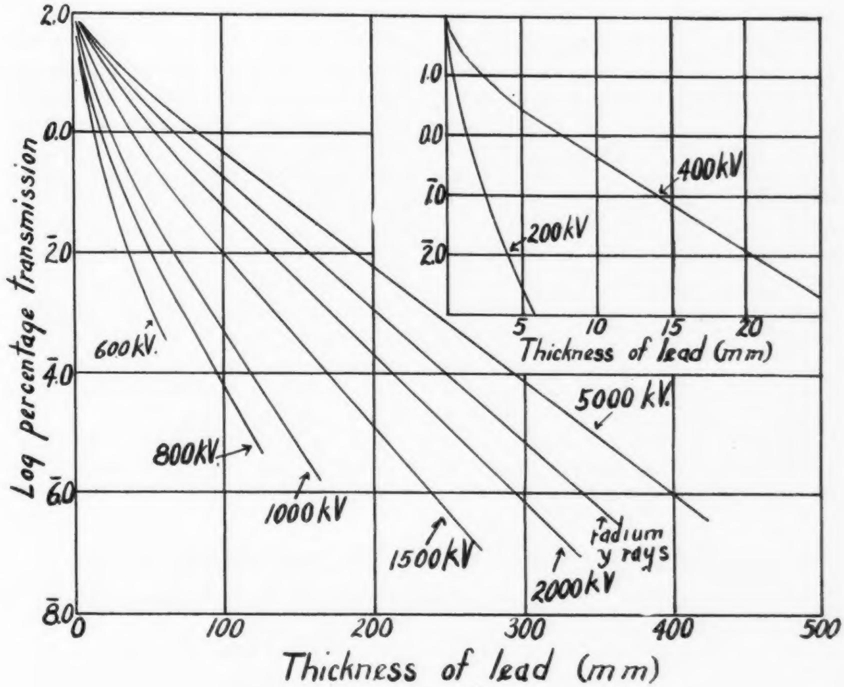


Fig. 6.

Absorption curves for radiation of various energies in lead.
From W. Binks, "Protection in Industrial Radiology." Brit. J. Radiology 16:49

ratio between the thicknesses of various building materials which are required to do the same shielding job in the intermediate range of x-ray voltages.

If you do your shielding with lead or concrete and operate your tube on the more common characteristics, several people have made the calculations which will simplify the estimation of what you need. Fig. 7[15] shows the thickness of lead required for tubes operating continuously at 10 milliamperes and at various voltages and distances from the point which is to be protected.

Fig. 8 is another way of getting at the same information with another factor included. This alignment chart[16] permits the easy calculation of lead thickness from the distance, potential and current of the tube in the medium to high voltage range.

Fig. 9[15] shows the same information put on a single graph requiring no manipulation for the medium and lower voltage ranges.

One further item must be added which complicates the whole picture most marvelously. Only the direct radiation from the tube has been considered as a hazard to the people working in the area in this whole discussion. Actually when the tube is in operation all of the objects in the line of the useful beam also become sources of secondary radiation. Under the proper conditions the back-scatter from the object being x-rayed may be greater than the scattered radiation from the tube itself. The scattered secondary radiation is always of a softer or less penetrating quality than the radiation from the primary beam but in these days of extremely high potential and high power it may still be a very dangerous form of radiation. Since the second-

ary radiation is scattered in all directions from the point at which it originates it is necessary to consider it at least as carefully as the primary beam in setting up the radiation protection. A further consideration is that at the higher potentials, above one million volts, there may be radiation of other sorts in addition to the secondary x-radiation.

Fig. 10[19] shows a situation in which the radiation actually received at a point will be higher than the calculation indicates should be found there. The set-up is simply a tube in one room and an ionization chamber, representing an occupant, in the next room. The tube is transmitting a broad beam in the direction of the ionization chamber and from the distance, the tube output and the thickness of the wall you could calculate what should be received by the chamber. That would account for the contribution of the primary beam, the amount which is represented by the two heavy lines from the source to the ionization chamber. In addition to this primary radiation there would also be secondary radiation from all of the building material through which the primary beam happened to pass. The secondary radiation is represented here by the lighter lines shown coming in from the building material in all directions. This sketch is not supposed to have any quantitive significance but it is realistic as to the nature of the problem.

The secondary radiation problem, of course, is only of practical importance where the voltage of the tube is high

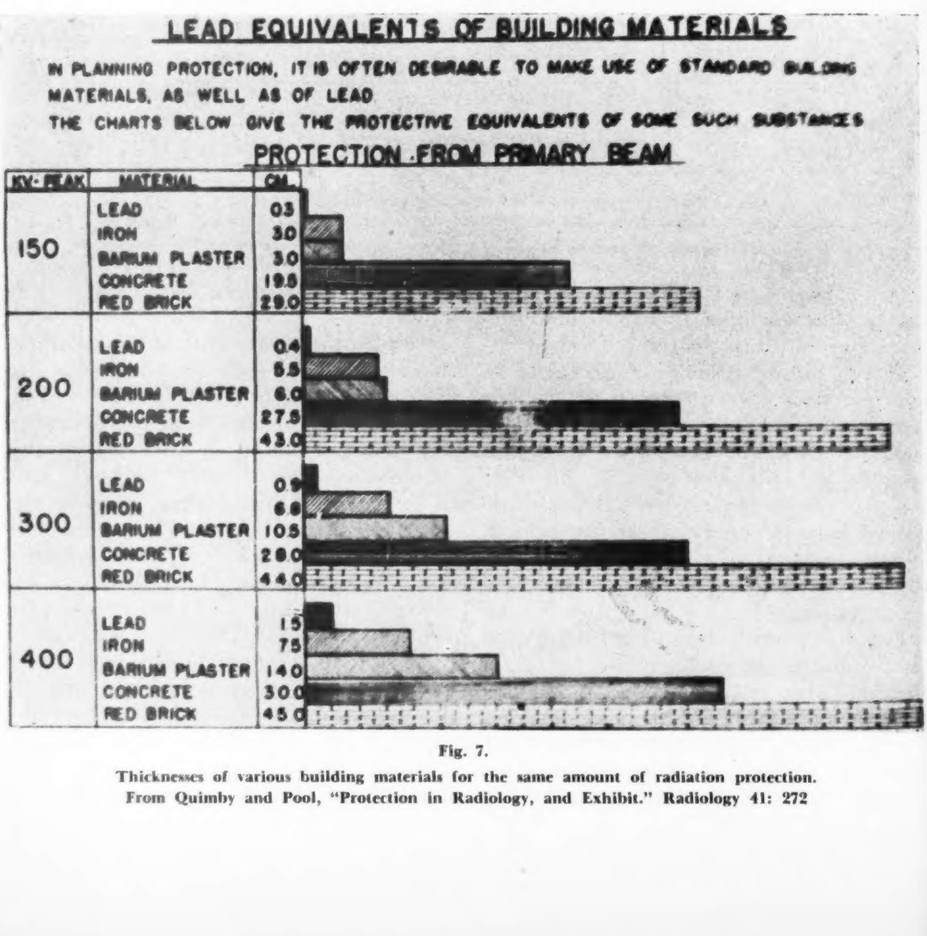


Fig. 7.

Thicknesses of various building materials for the same amount of radiation protection. From Quimby and Pool, "Protection in Radiology, and Exhibit." Radiology 41: 272

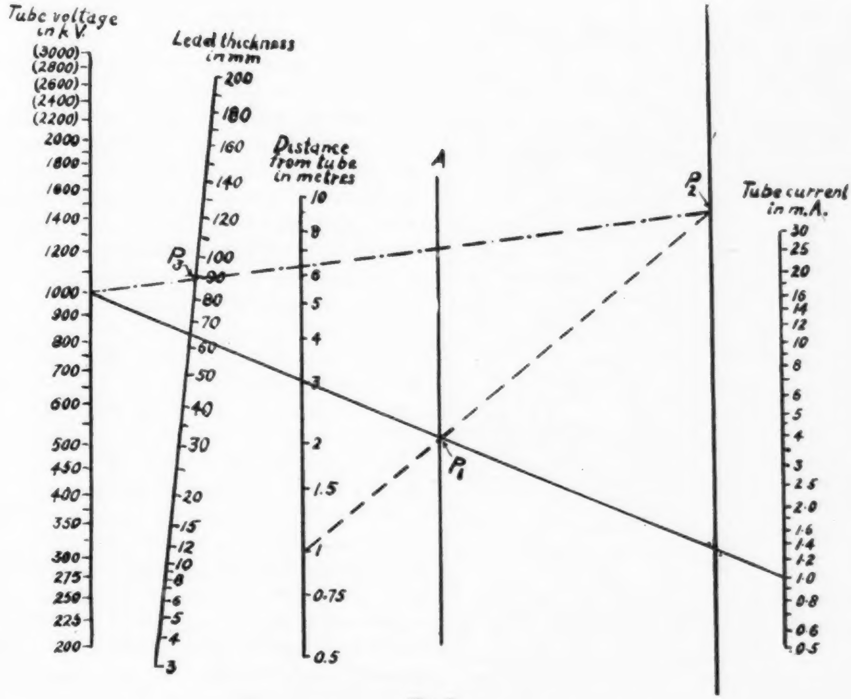


Fig. 8.

A Nomograph for the calculation of lead protection from x-rays.
From W. Binks, "A Nomogram for the determination of Lead Protection against High Voltage X-Rrays." Brit. J. Radiology 13:322-323 (Sept. 1940)

enough that the secondaries will have some significant penetration. It would not have any significance if the primary source were a crystalographic tube with only enough penetration in the primary to produce skin effects.

The whole situation can probably be best summed up in a few practical applications. Fig. 11[18] is a diagram of a mobile industrial unit with a 400-kilovolt head. It was being used for the inspection of welds at the time that the radiation survey was made. The figures on the diagram at various places are the radiation dosages per eight-hour day. Those in circles are dosages with the shutter closed but the tube operating. The others are dosages with the shutter open and the tube operating. This is an example of good industrial practice in which the operator is protected by a complete enclosure while the tube is in operation and it will be noticed that the dosages within the enclosure are of the order of 1/5 the tolerance dose except right at the wall of the enclosure next to the tube where it is just at the tolerance dose. It will also be noted that there are number of locations around the truck where the dosage rate is four to five times the tolerance whether the shutter is open or closed and that the rate within the boiler is 67 times the tolerance dose with the shutter open.

The rate of dosage within the boiler would not appear to be a matter of any importance but there are records of injuries from people going directly into the path of the useful beam to make adjustments with the tube in operation. It is practically very difficult to believe that

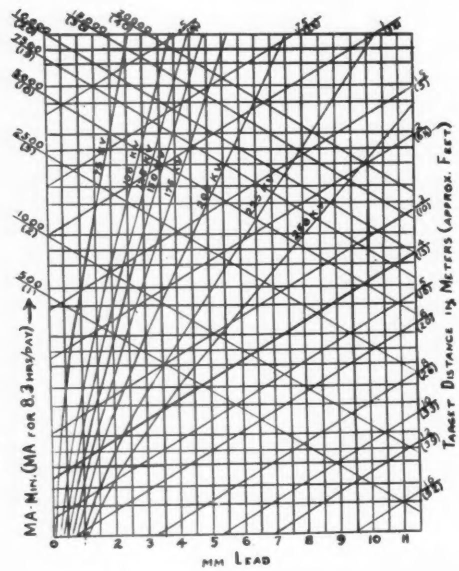


Fig. 9.

Curves for the calculation of lead protection against x-ay tubes at various potentials, currents and distances.

From C. B. Braestrup, "Industrial Radiation Hazards." Radiology 43;286-292 (Sept. 1944)

there is any harm in going into such a place and there is no sound and no sensation to warn of the danger. Accordingly, no one should be permitted to come closer than two meters from the tube while it is in operation.

One of the early high-voltage installations was an example of why a certain amount of experience is required in the installation of protective barriers and also why such installations should be thoroughly monitored after completion.

In this instance the control room and the dark room for developing the films were side by side and behind a protective barrier which was penetrated by a maze. After the tube had been in operation for about a week the operators began to notice that the plates he was using were badly fogged. An investigation showed that while the barrier had had installed and was quite adequate for the voltage being used it had not been considered necessary to carry it over the roof of the single story building and a significant amount of secondary radiation from the sheet iron on plank roof was penetrating both into the dark room and into the control room.

Industrial hygiene personnel should see to it that a real inspection of the shielding arrangements on any such installation is carried out by someone competent both when the installation is new and whenever a structural change is made in it or when a change is made in the nature of the material being examined.

We can also monitor the people working in the area in a fairly adequate manner with film badges which can now be obtained from Eastman or du Pont or by the use of one of the commercial badge services. One type contains a film sensitive to the radiation in use and an echelon will give an indication of the quality of radiation which has affected the film. This is of considerable importance since it makes a lot of difference in the corrective steps whether the film was blackened by a short exposure to the primary beam or by a long exposure to soft secondary radiation.

These films should be worn for a week and then developed. Exact directions as to the developing procedure comes with the films. If you object to going into this type of work, which necessarily includes permanently filing the film records, it is possible to get the film developed, interpreted and filed by companies specializing in that type of service.

It is possible to obtain much information about radiation with a device as simple as

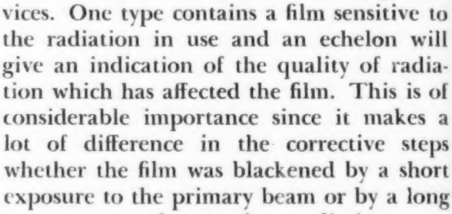


Fig. 10.

Diagram of the production of secondary radiation from the material of the building.

From Singer, Braestrup and Wycoff, "Absorption Measurements for Broad Beams of 1 and 2 Megavolt X-Rays"

a dental x-ray film fastened to the clothing with a paper clip. The paper clip will act as a shield for part of the film as well as a fastener.

Whatever type of film monitor is used it is of considerable importance that some of the films be fastened to the wrist or hand in most industrial work as the hands are commonly the first spot to be injured.

If the film monitoring is carefully done and a comparison made with films exposed to various known amounts of radiation and developed in the same way as the monitor films, the test is roughly quantitative and will give an idea of the exposure which has been received.

In addition to the film monitoring it is possible to obtain an ionization electroscope the size of a fountain pen which can be carried in the clothing and which will give a direct reading of the exposure daily. These devices should be read at the end of every shift and if they show an excessive exposure the film badge should be developed immediately as a check.

Physical examinations of people potentially exposed to radiations should always be carried out regularly. Examination of the hands for thickening of the skin and brittleness of the nails is particularly important. The present tendency seems to be to minimize the importance of blood counts for the discovery of early signs of radiation injury but they will certainly show the earliest available signs of whole body irradiation.

TABLE II.
LEAD THICKNESS REQUIRED FOR PRIMARY PROTECTIVE BARRIERS FOR OPERATION AT 10 MILLIAMPERES AND AT THE DISTANCE AND KILOVOLTAGE INDICATED.

Target distance		100 kv peak		150 kv peak		200 kv peak	
ft.	m.	mm.	in.	mm	in.	mm	in.
1	0.31	3.8	0.165	4.6	0.181	9.8	0.386
2	0.61	3.2	0.126	4.0	0.157	6.2	0.244
3	0.91	2.9	0.114	3.7	0.146	5.7	0.224
4	1.22	2.7	0.106	3.4	0.134	5.3	0.209
5	1.52	2.6	0.102	3.3	0.130	5.0	0.197
10	3.05	2.1	0.083	2.7	0.106	4.1	0.161
20	6.10	1.6	0.063	2.2	0.087	3.2	0.126
50	15.24	0.9	0.035	1.4	0.055	2.1	0.083
100	30.48	0.6	0.024	0.9	0.035	1.4	0.055

Adapted from Safety Code for the Industrial Use of X-Rays, American War Standard Z54. 1-1946; given in more detail and with corrections for some other milliampereages in the original.

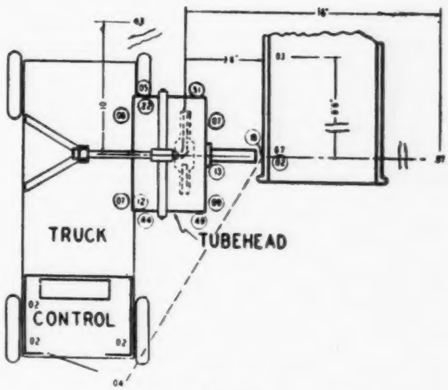


Fig. 11.

Radiation survey of 400 kilovolt mobile industrial x-ray unit.

From C. B. Braestrup, "X-ray Protection in Diagnostic Radiology." Radiology 38:207-216 (Feb. 1942)

Finally, anyone who has this problem to contend with should get a copy of the American Standards Association Code Z54.1-1945 and study it religiously. It contains a world of reliable information on precautionary measures to be taken to prevent radiation injury. In the last analysis, radiation injury will only be prevented by everyone involved making himself thoroughly familiar with the hazards and the means of avoiding them. This type of injury is particularly insidious in that one is not even made uncomfortable in the process of acquiring a fatal exposure. Such instances as a man losing his hand and later his life by deliberately holding it in front of a fluoroscope or instances of destroying the hands of others by permitting them to be held in front of the fluoroscope will be prevented only by a thorough process of education. They are completely unnecessary.

Radiation is a tool whose potentialities are only beginning to be appreciated. We are all going to see a lot more of it in the future than we have in the past and if we spend only a little time finding out its potentialities for harm, that acquaintanceship will be pleasant and useful. If we

remain in blissful ignorance we can be perfectly sure that it will be tragic.

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